

Collective Dynamics in High-Energy Nuclear Collisions

(Formation of the Strongly Coupled QGP at RHIC)

Nu Xu

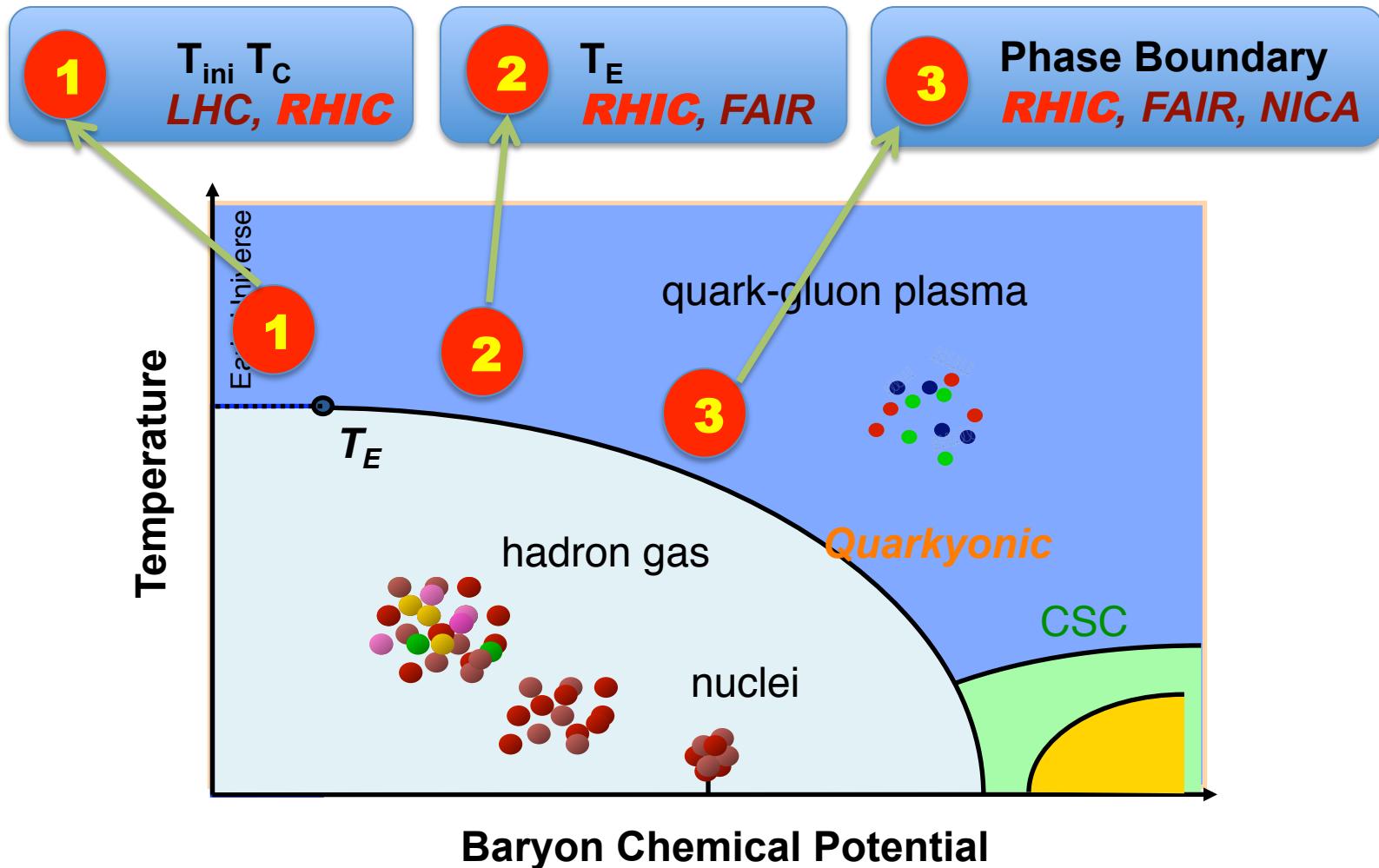
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Many Thanks to the Organizers!

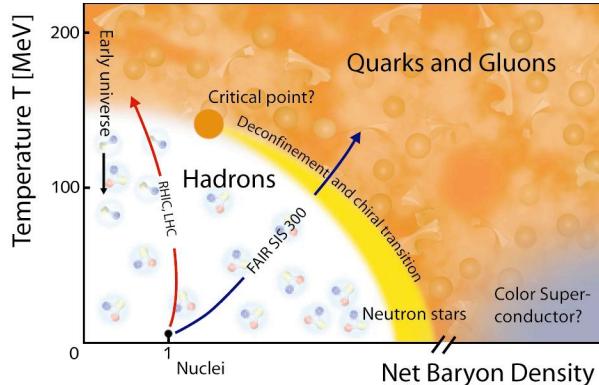
*H. Masui, B. Mohanty, H.G. Ritter, S. Shi, A. Tang, K.Wu
and some theorists*



The QCD Phase Diagram and High-Energy Nuclear Collisions



Physics Focus

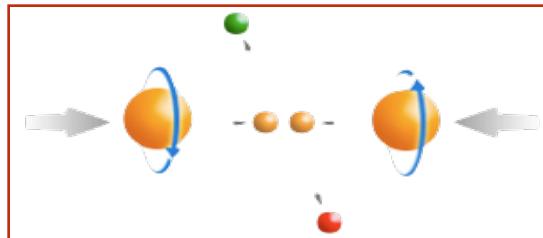


1) At 200 GeV top energy

- Study **medium properties, EoS**
- pQCD in hot and dense medium

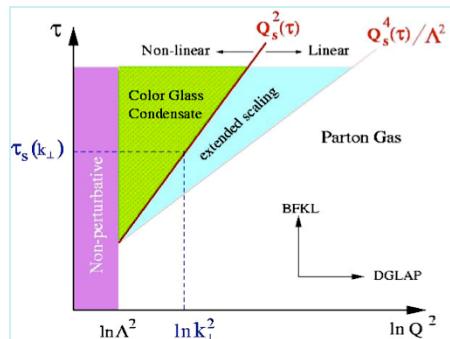
2) RHIC beam energy scan

- Search for the ***QCD critical point***
- Chiral symmetry restoration



Polarized spin program

- Study **proton intrinsic properties**



Forward program

- Study low-x properties, search for **CGC**
- Study elastic (inelastic) processes (pp2pp)
- Investigate **gluonic exchanges**



Outline

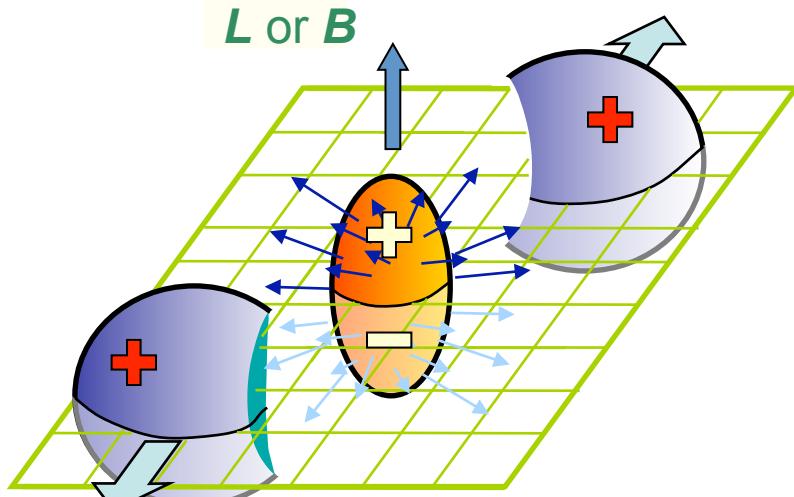
(1) Recent results from RHIC

- Search for the Local Parity Violation
- Nuclear modification factor, open issues
- Collective expansion, open issues

(2) Future directions for exploring the QCD phase diagram

- 200 GeV: Thermalization, T_C , energy loss (u, d, s, c)
- BES: search for T_E and the possible *phase boundary*

Search for Local Parity Violation in High Energy Nuclear Collisions



The separation between the same-charge and opposite-charge correlations.

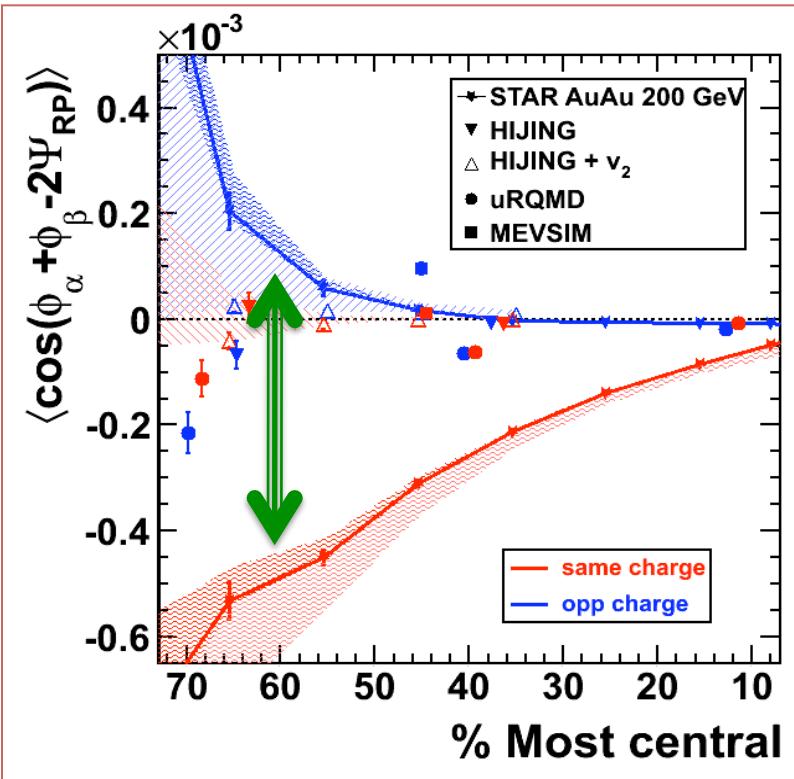
- Strong external EM field
- De-confinement and Chiral symmetry restoration

$$\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle$$

Parity even observable

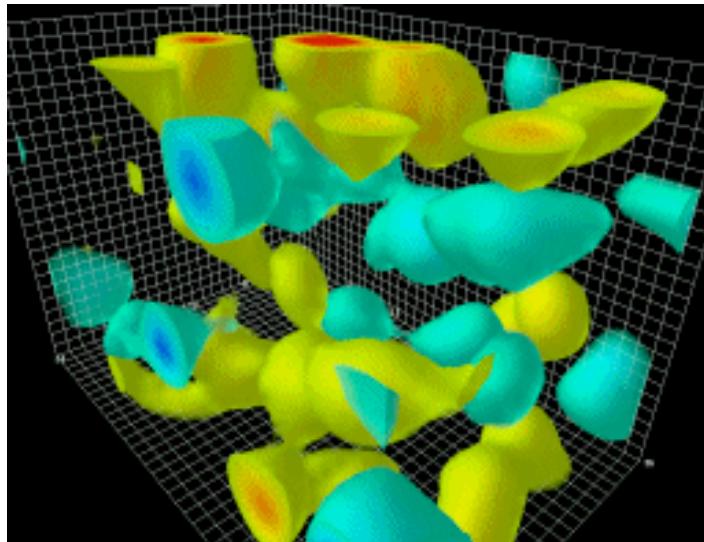
Voloshin, PR C62, 044901(00).

STAR; arXiv: 0909.1739 (PRL); 0909.1717 (PRC).



Search for Local Parity Violation in High Energy Nuclear Collisions

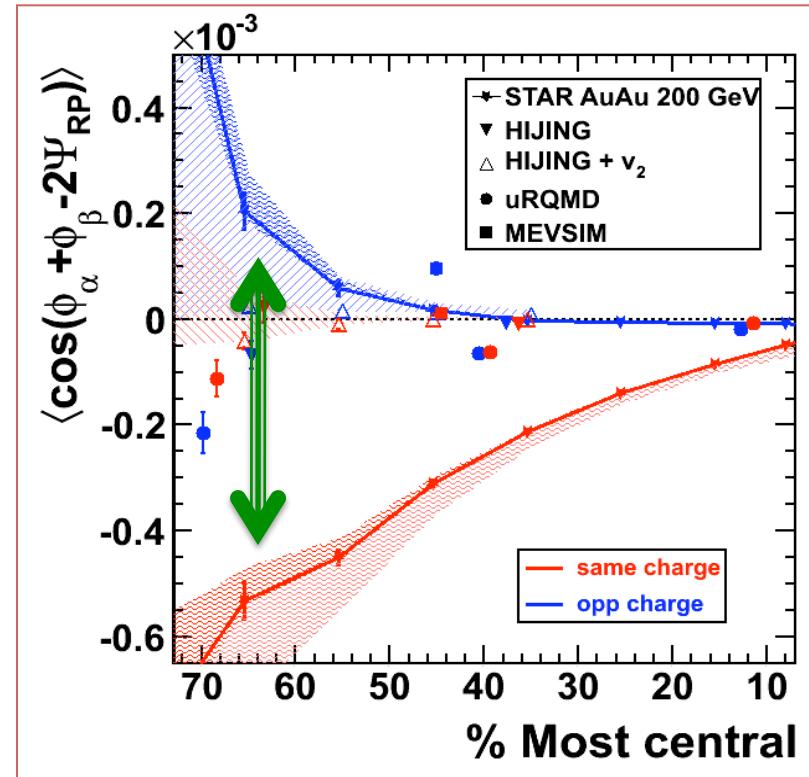
Animation by Derek Leinweber



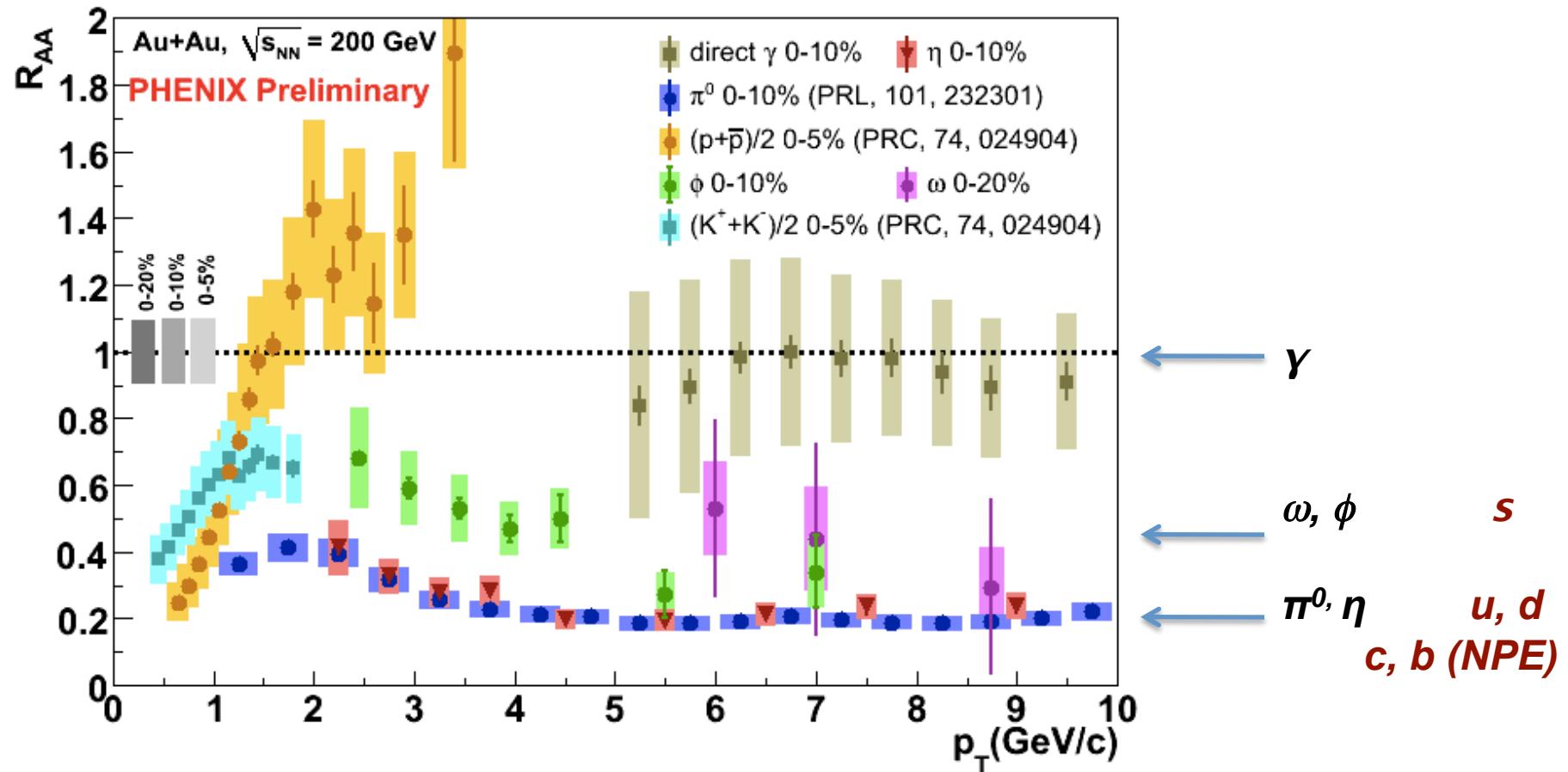
Chiral Magnetic Effect:

- Kharzeev, PL B633 260 (2006).
- Kharzeev, Zhitnitsky, NP A797 67(07).
- Kharzeev, McLerran, Warringa, NP A803 227(08).
- Fukushima, Kharzeev, Warringa, PR D78, 074033(08).

Topological transitions have never been observed *directly* (e.g. at the level of quarks in DIS). An observation of the *spontaneous strong* parity violation would be a clear proof for the existence of such physics.



Nuclear Modification Factor R_{AA}

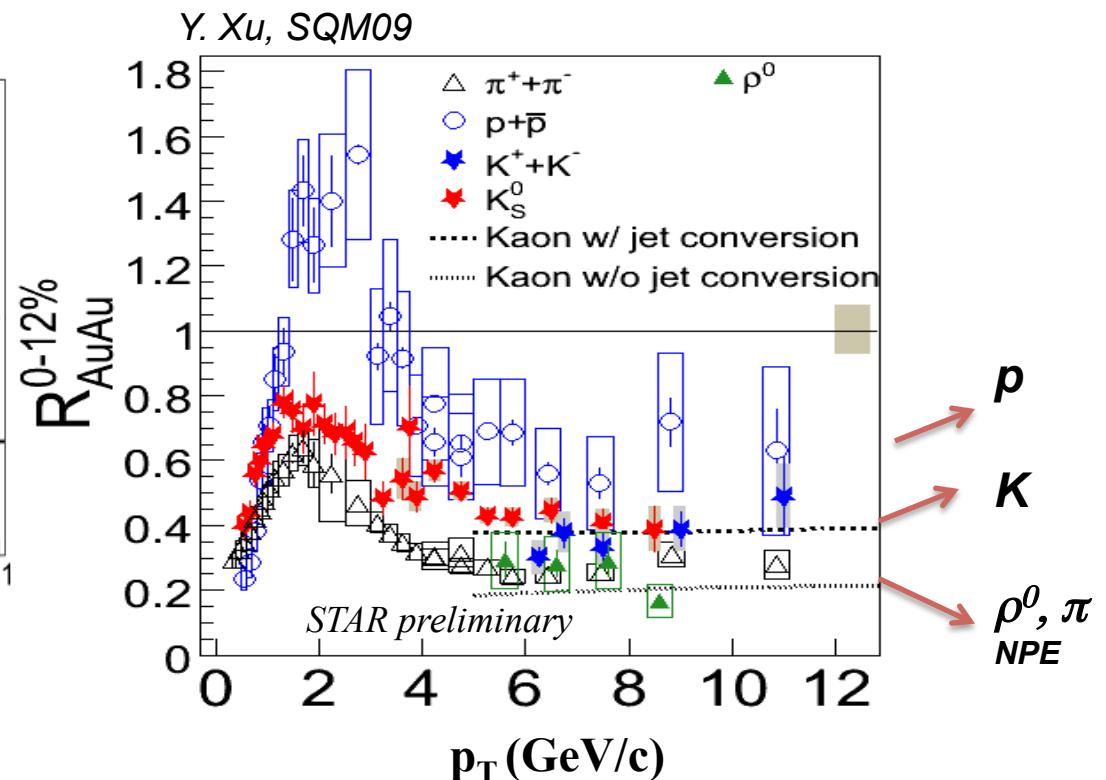
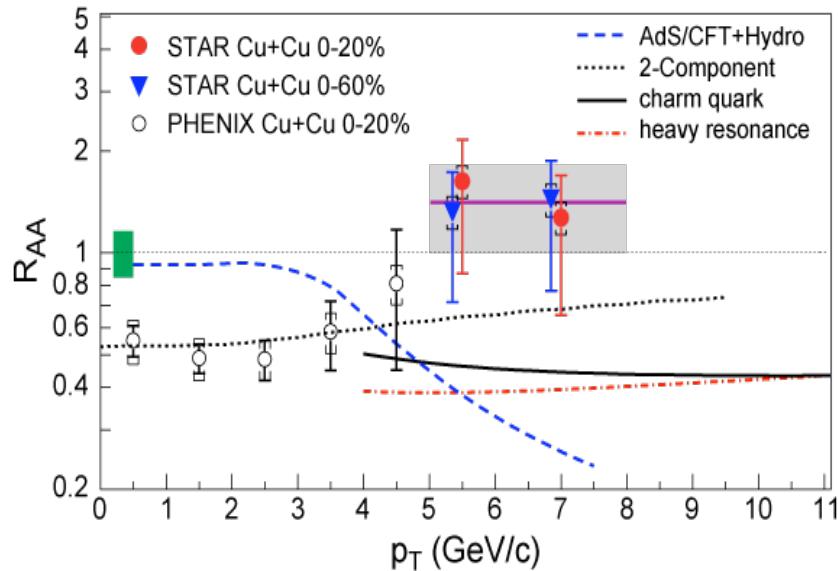


S. Esumi, M. Neglis et al.



Nuclear Modification Factor R_{AA}

STAR: PRC®, 0904.0439

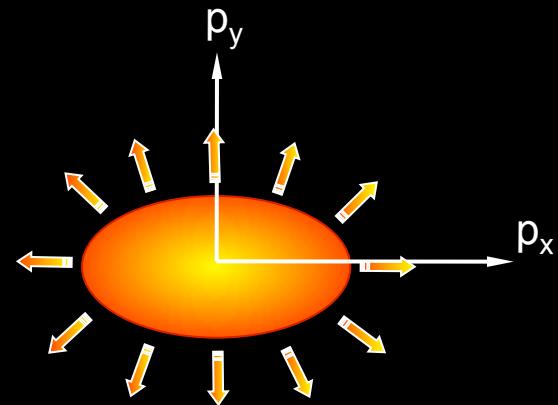
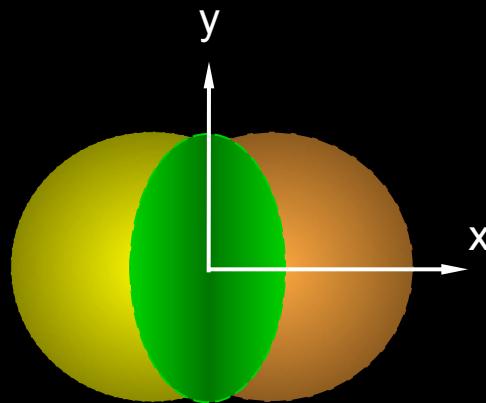


- 1) Flavor ?: $R_{AA}(\pi) \sim R_{AA}(\rho^0) < R_{AA}(\phi) < R_{AA}(J/\psi)$
- 2) Mass ? $R_{AA}(\pi) < R_{AA}(K) < R_{AA}(p)$

Challenges to pQCD calculations

Anisotropy Parameter v_2

coordinate-space-anisotropy \Leftrightarrow momentum-space-anisotropy

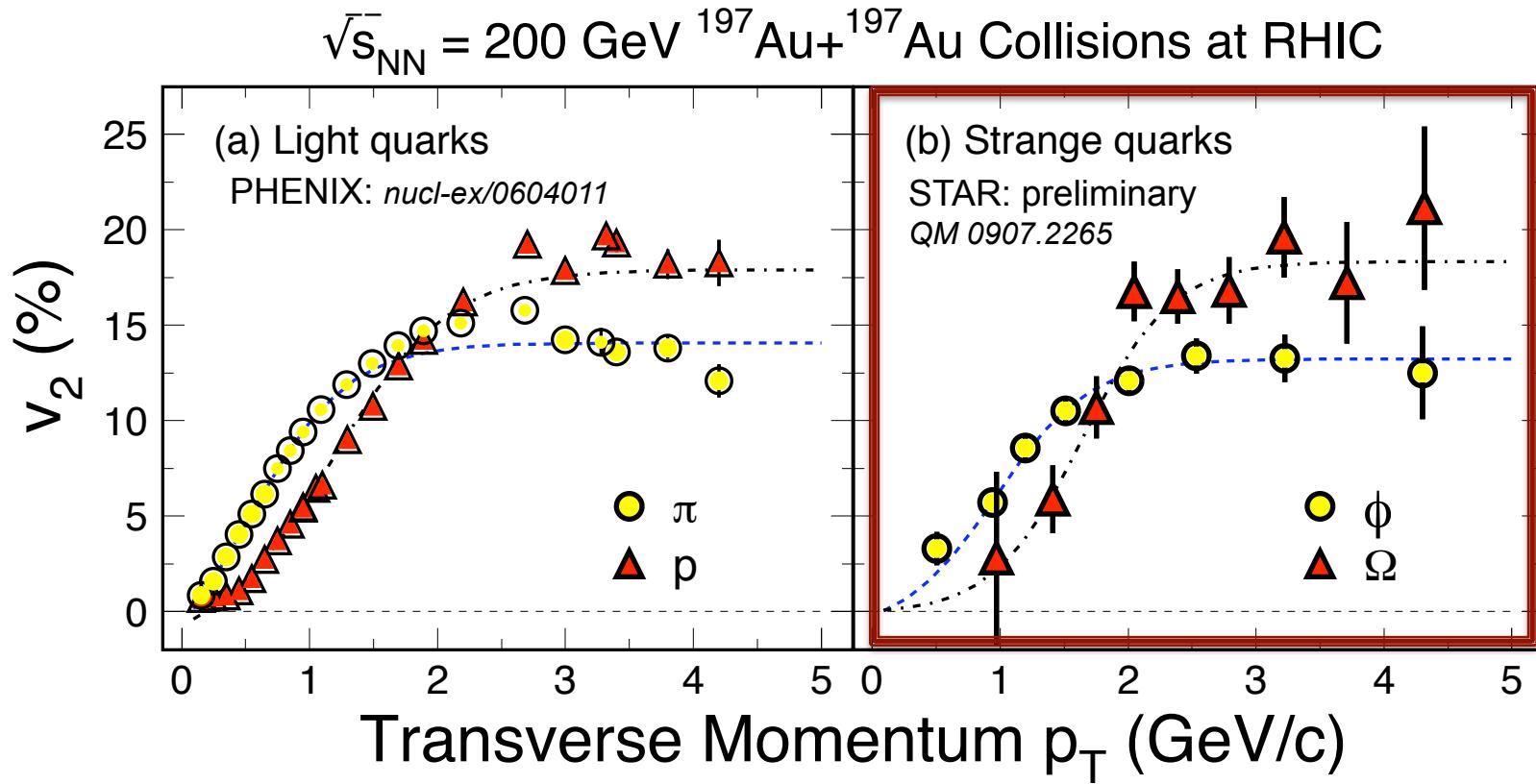


$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

$$v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1} \left(\frac{p_y}{p_x} \right)$$

Initial/final conditions, EoS, degrees of freedom

Partonic Collectivity at RHIC



Low p_T ($\leq 2 \text{ GeV}/c$): hydrodynamic mass ordering

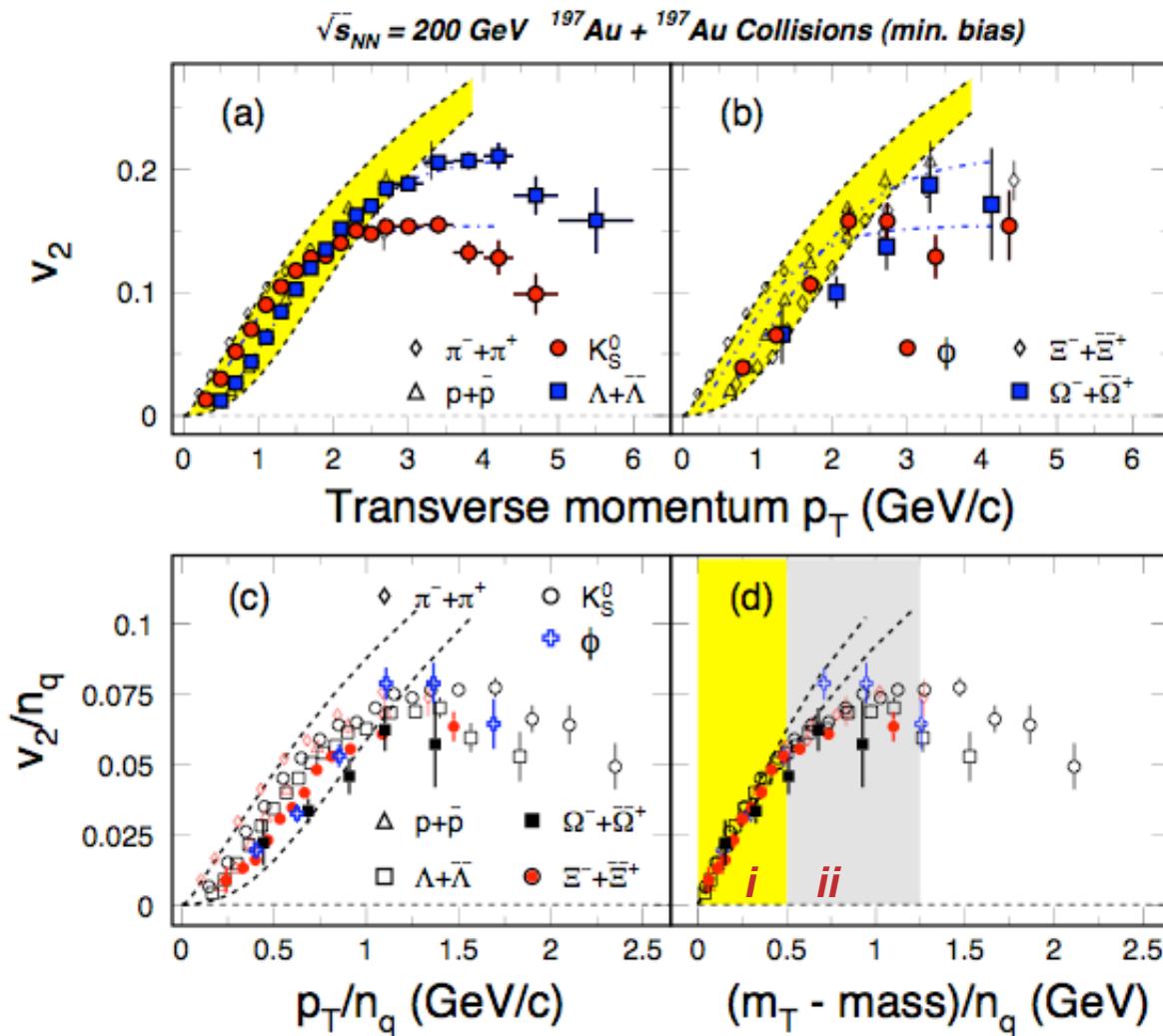
High p_T ($> 2 \text{ GeV}/c$): number of quarks ordering

s-quark hadron: smaller interaction strength in hadronic medium

light- and s-quark hadrons: similar v_2 pattern

=> Collectivity developed at partonic stage!

Collectivity, De-confinement at RHIC



- v_2 of light hadrons and multi-strange hadrons
- scaling by the number of quarks

At RHIC:

- ➡ **n_q -scaling**
novel hadronization process
- ➡ **Partonic flow**
De-confinement

PHENIX: PRL **91**, 182301(03)

STAR: PRL **92**, 052302(04), **95**, 122301(05)
nucl-ex/0405022, QM05

S. Voloshin, NPA715, 379(03)

Models: Greco et al, PRC **68**, 034904(03)

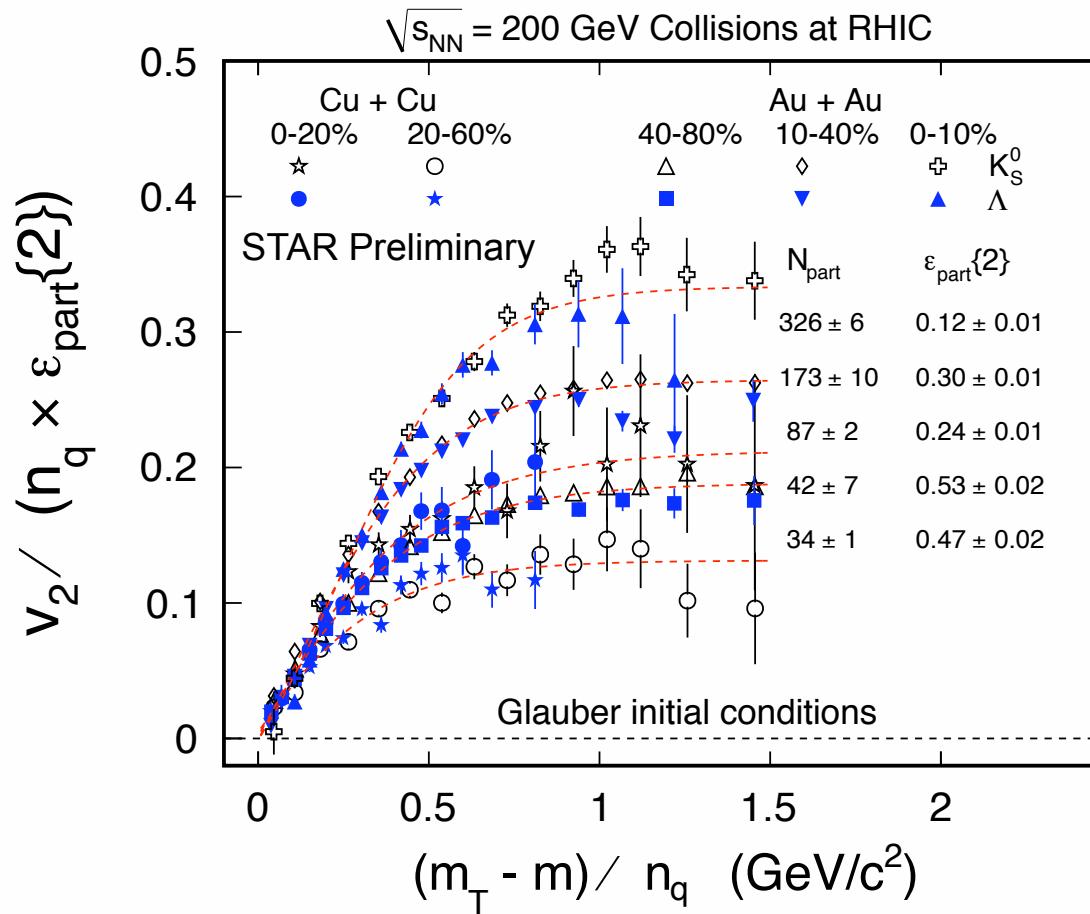
Chen, Ko, nucl-th/0602025

Nonaka et al. PLB **583**, 73(04)

X. Dong, et al., Phys. Lett. **B597**, 328(04).

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System Size Driven Collectivity



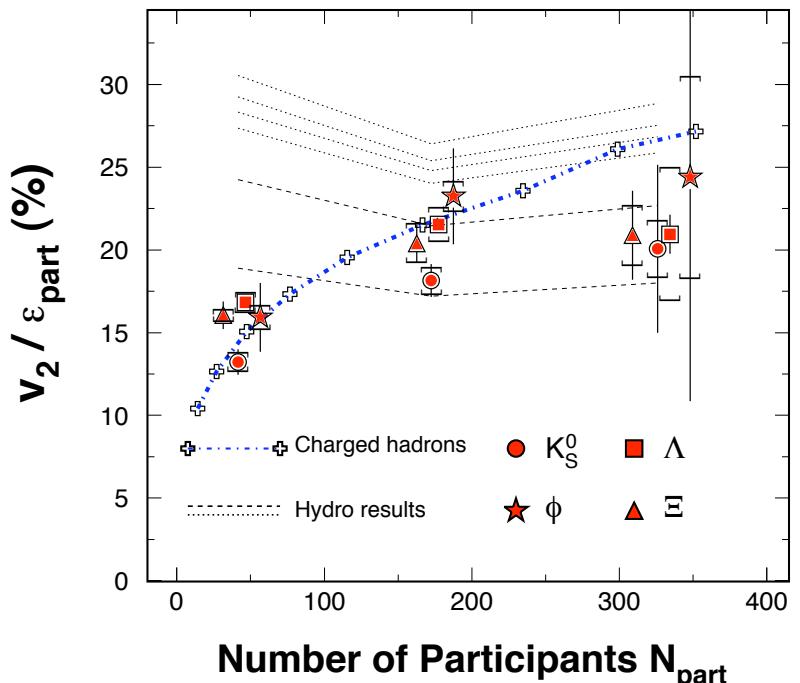
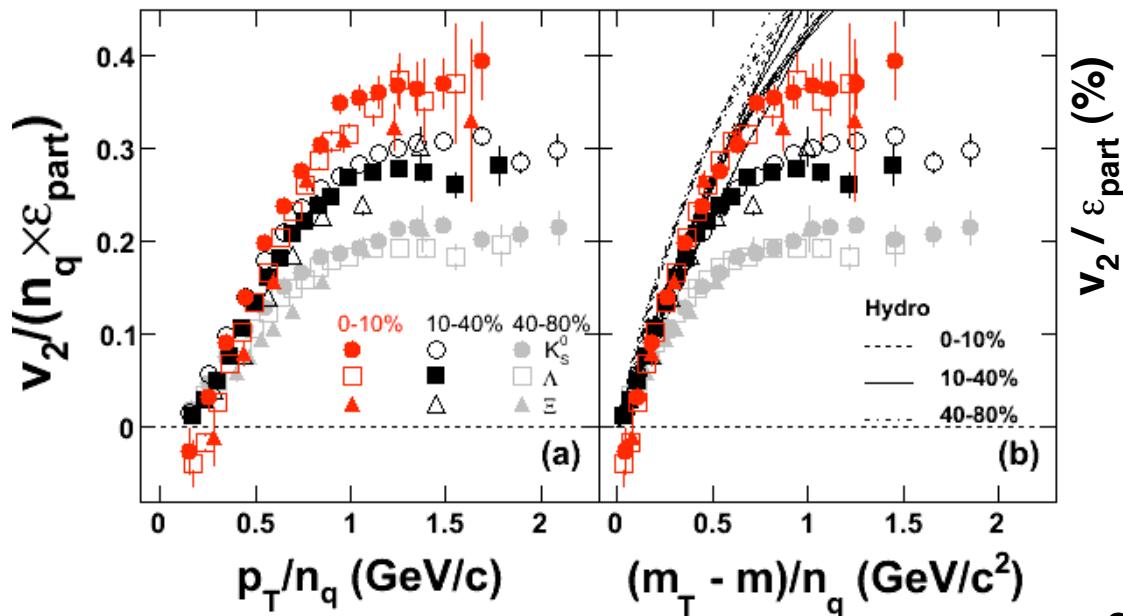
Collectivity: Driven by number of participants,
NOT by eccentricity.

Caution: Local equilibrium and perfect fluid

200 GeV: v_2 Centrality Dependence

STAR: Phys. Rev. **C77**, 54901(2008)

200 GeV Au+Au



S. Voloshin, A. Poskanzer, PL **B474**, 27(00).
D. Teaney, et. al., nucl-th/0110037

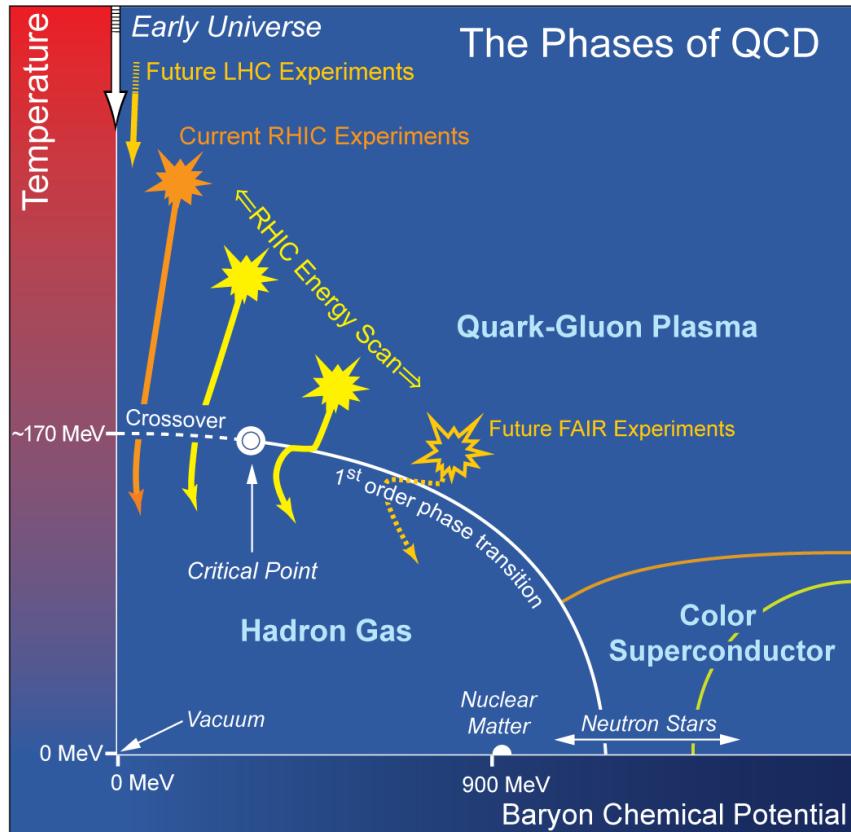
- Larger $v_2 / \varepsilon_{\text{part}}$ indicates stronger flow in more central collisions.
- **NO** $\varepsilon_{\text{part}}$ scaling.
- The observed n_q -scaling does not necessarily mean thermalization, viscosities?!

- (1) Hadron *type* dependence of the nuclear modification factor.
- (2) Strong collectivity, *for all hadrons*. N_{part} driven. The ideal hydro limit Not reached.

What is the next?

- Direct detection of heavy flavor hadrons
- Direct gamma and di-leptons
- Beam Energy Scan!
- ...

The QCD Phase Diagram and the CP



RHIC (200) & LHC: Determine the temperature T_{init} , T_c

BES: Explore the QCD phase diagram T_E and the location of *phase boundary*

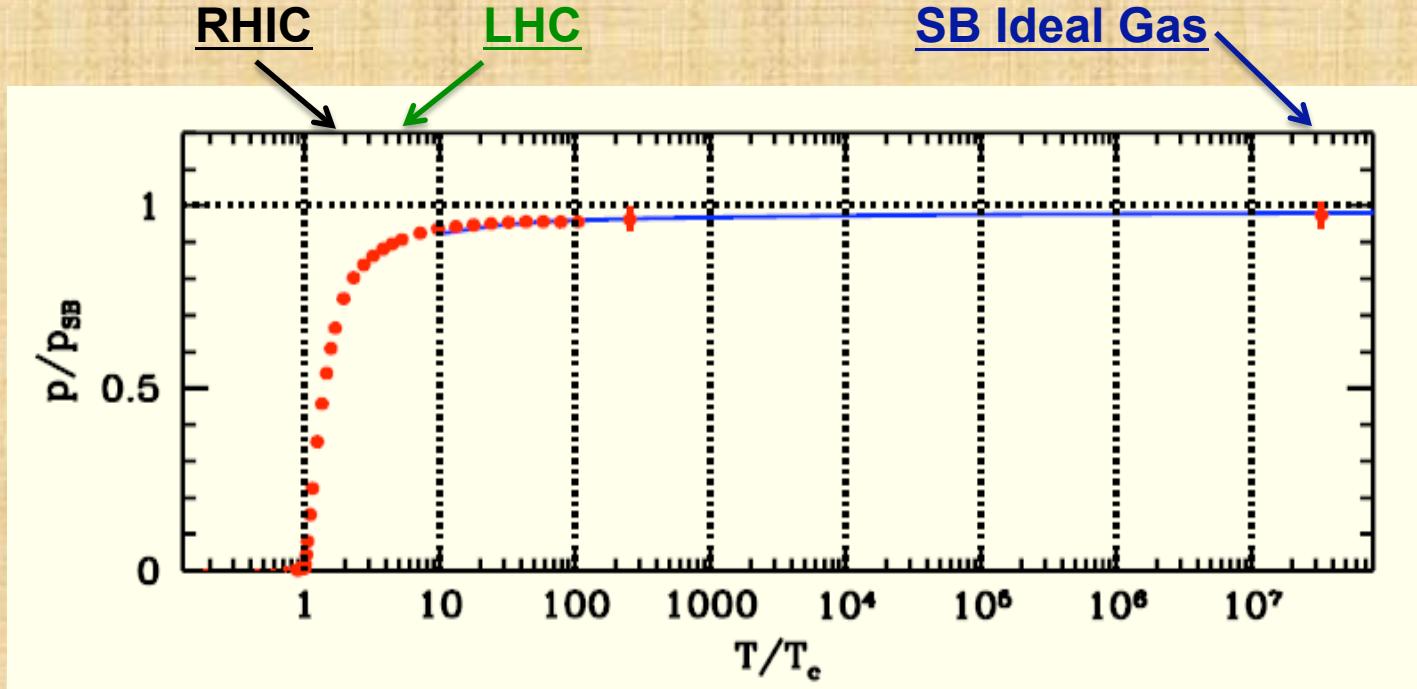
- LGT prediction on the transition temperature T_c is robust.
- LGT calculation, universality, and models hinted the existence of the critical point on the QCD phase diagram* at finite baryon chemical potential.
- Experimental evidence for either the critical point or 1st order transition is important for our knowledge of the QCD phase diagram*.

* *Thermalization has been assumed*

M. Stephanov, K. Rajagopal, and E. Shuryak, *PRL* **81**, 4816(98); K. Rajagopal, *PR* **D61**, 105017 (00)

<http://www.er.doe.gov/np/nsac/docs/Nuclear-Science.Low-Res.pdf>

QCD Thermodynamics



- 1) At $\mu_B = 0$: cross over, $150 < T_c < 200 \text{ MeV}$
- 2) The SB ideal gas limit: $T/T_c \sim 10^7$
- 3) $T_{ini}(\text{LHC}) \sim 2\text{-}3 * T_{ini}(\text{RHIC})$
- 4) Thermodynamic evolutions are similar for RHIC and LHC**

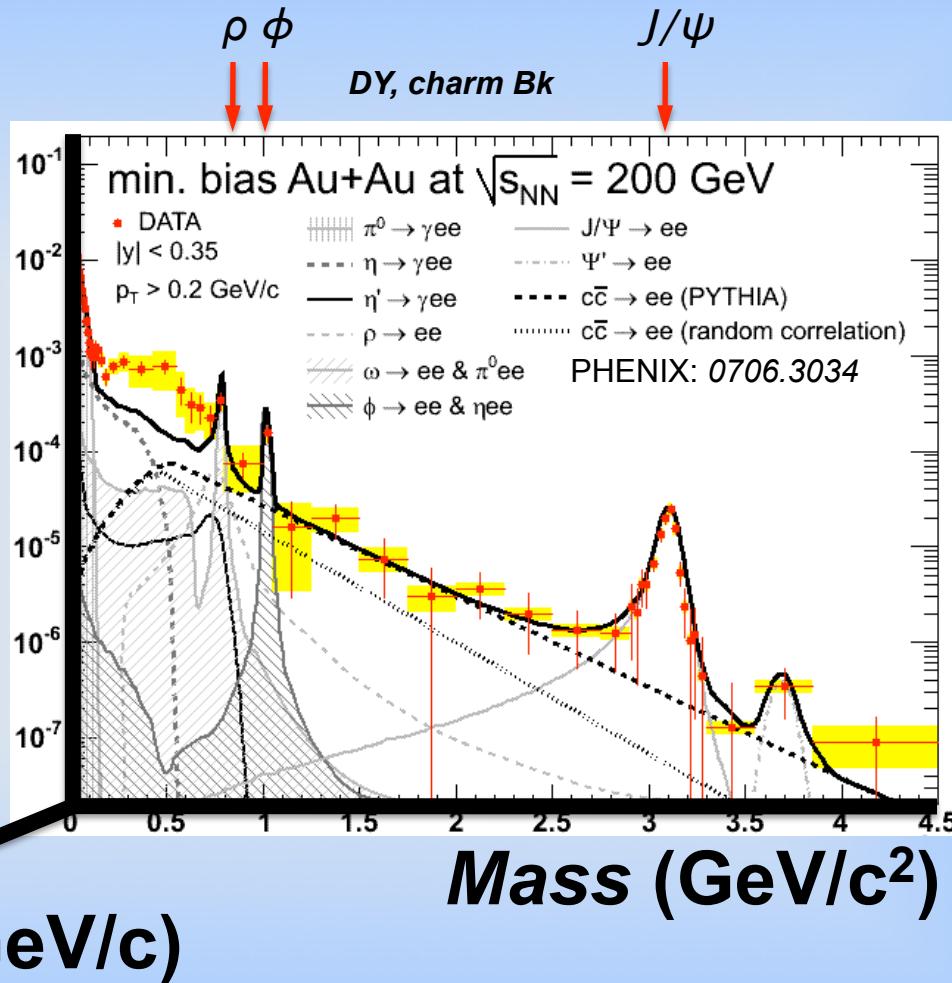
Zoltan Fodor, Lattice 2007

The di-Lepton Program

(1) σ, m

(2) v_2

(3) R_{AA}

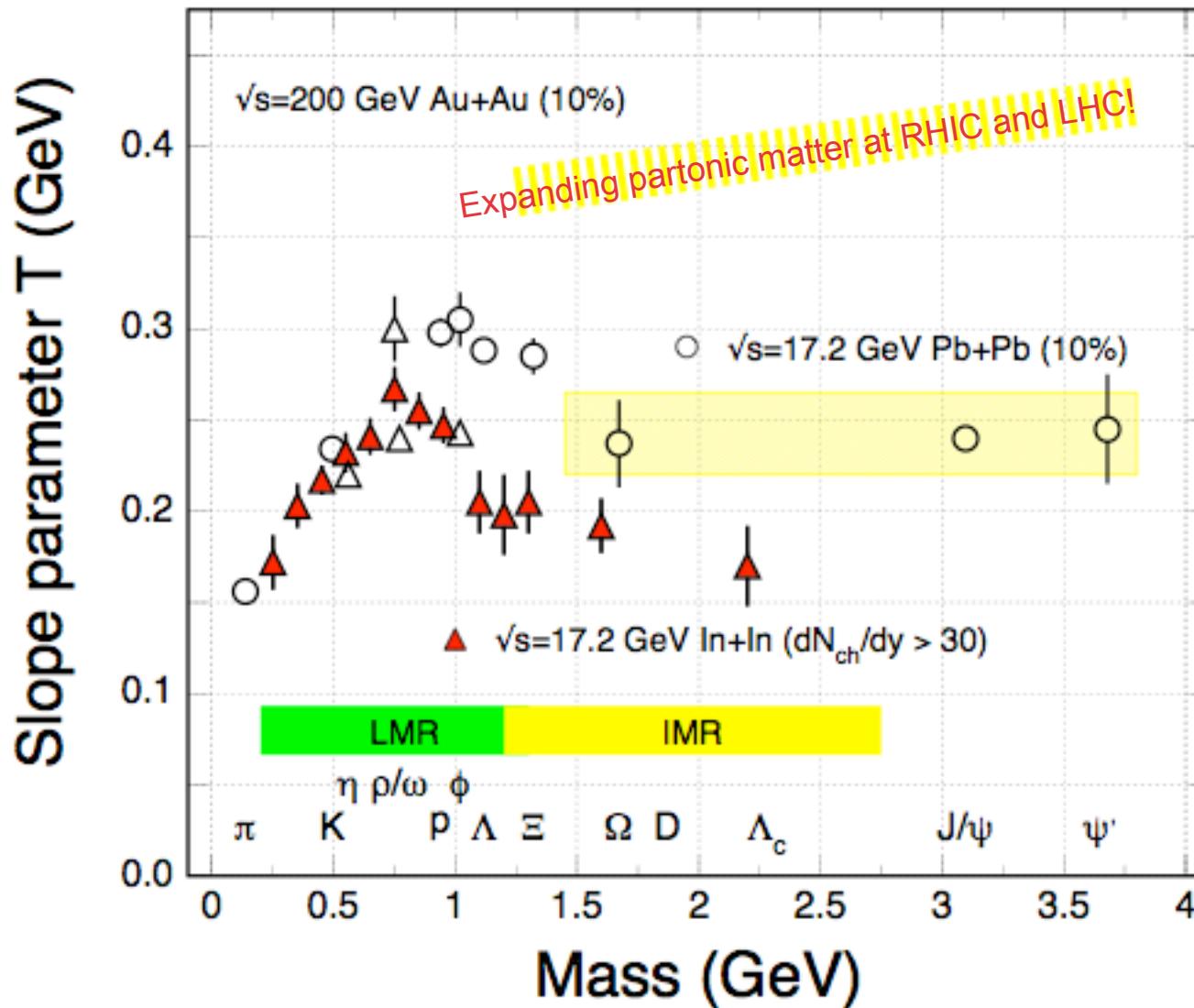


✓ Chiral Symmetry Restoration (may be)

✓ Direct Radiation from The Hot/Dense Medium

PHENIX: HBD
STAR: Full ToF Vertex detectors

Direct Radiation



Di-leptons allow us to measure the direct radiation from the matter with partonic degrees of freedom, no hadronization!

- Low mass region:

$$\rho, \omega, \phi \Rightarrow e^-e^+$$

$$m_{inv} \Rightarrow e^-e^+$$

*medium effect
Chiral symmetry*

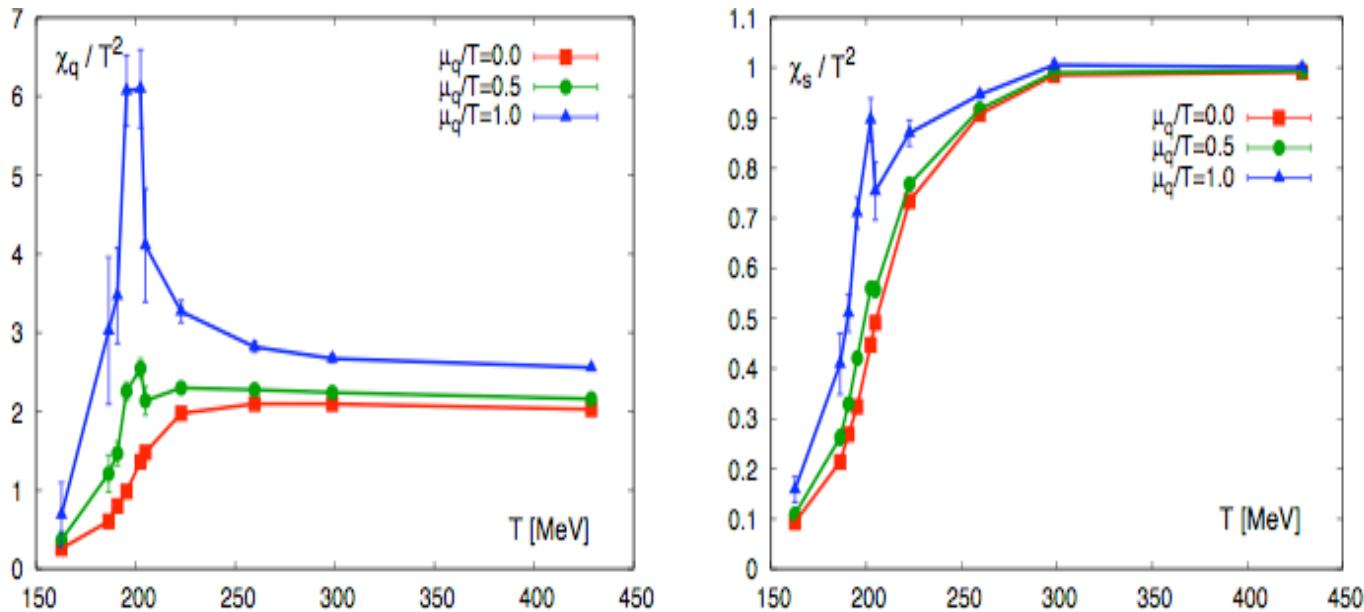
- High mass region:

$$J/\psi \Rightarrow e^-e^+$$

$$m_{inv} \Rightarrow e^-e^+$$

Direct radiation

Observables: χ_q , χ_s



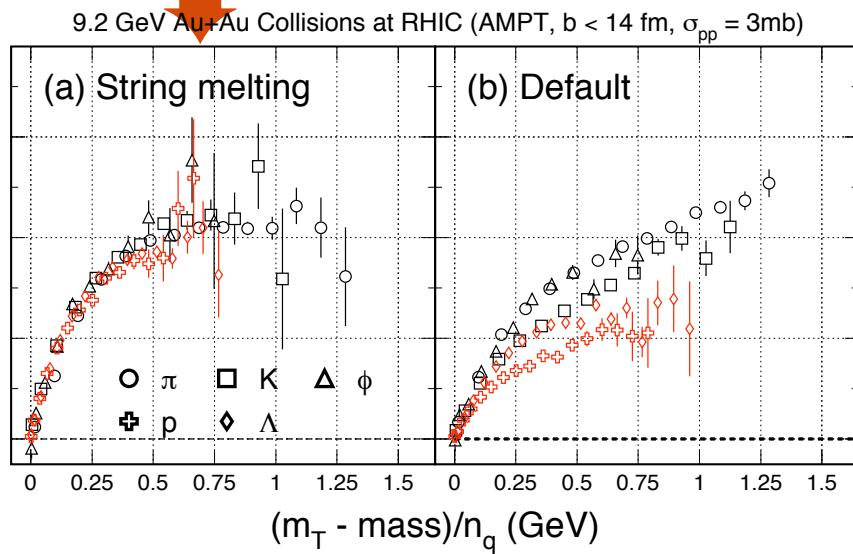
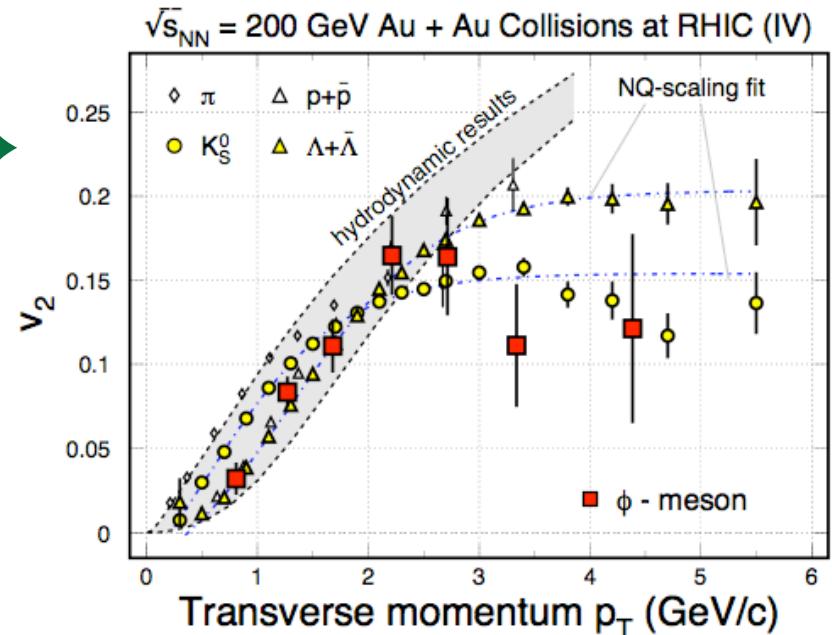
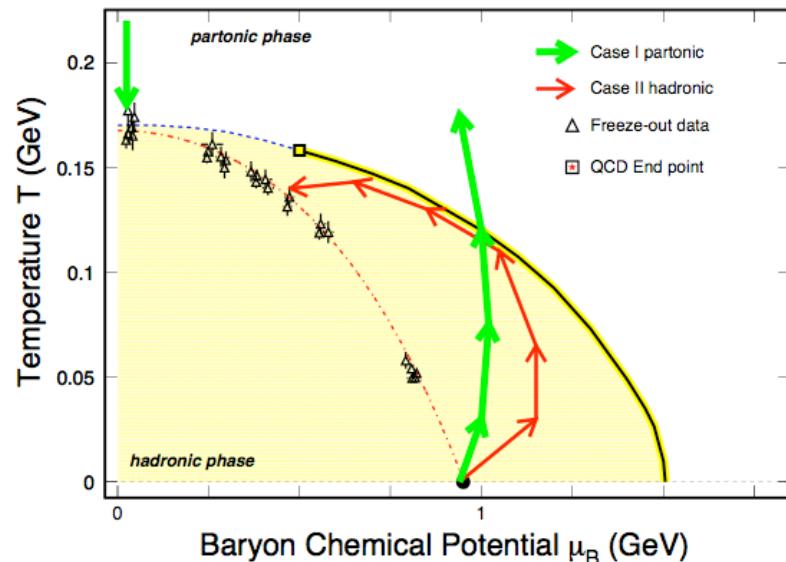
Event by event:

1. net-proton Kurtosis $K_p(E)$
2. two proton correlation functions $C_2(E)$
3. ratio of the d/p
4. ratio of K/p

$$K_p = \frac{\langle N_p^4 \rangle - 3\langle N_p^2 \rangle^2}{\langle N_p^2 \rangle}$$

M. Cheng et al., PRD79, 074505(09);arXiv:0811.1006
 F. Karsch, INT, 08
 M. A. Stephanov, PRL102, 032301(09)

Observable: Quark Scaling



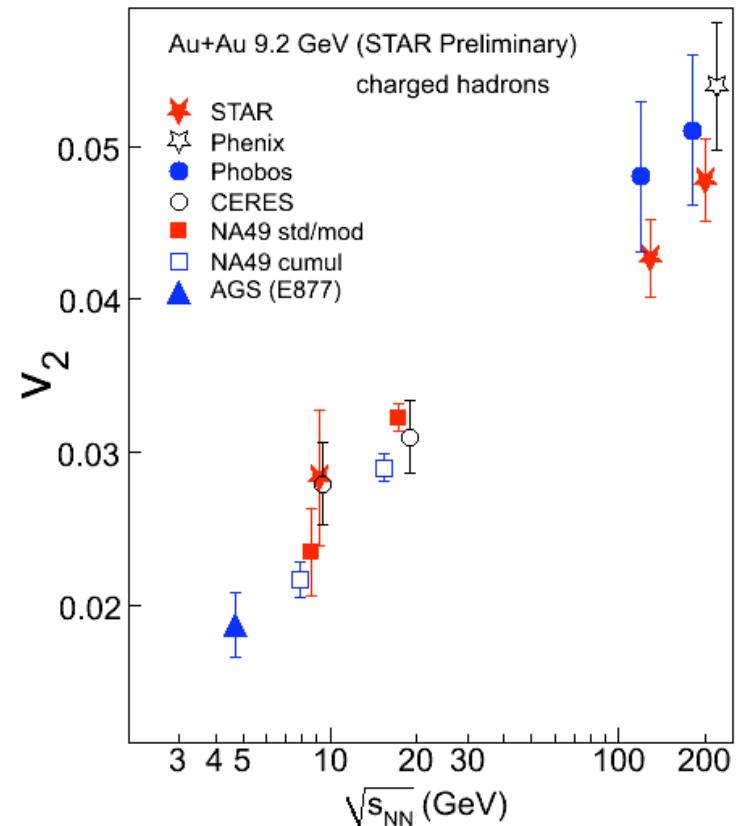
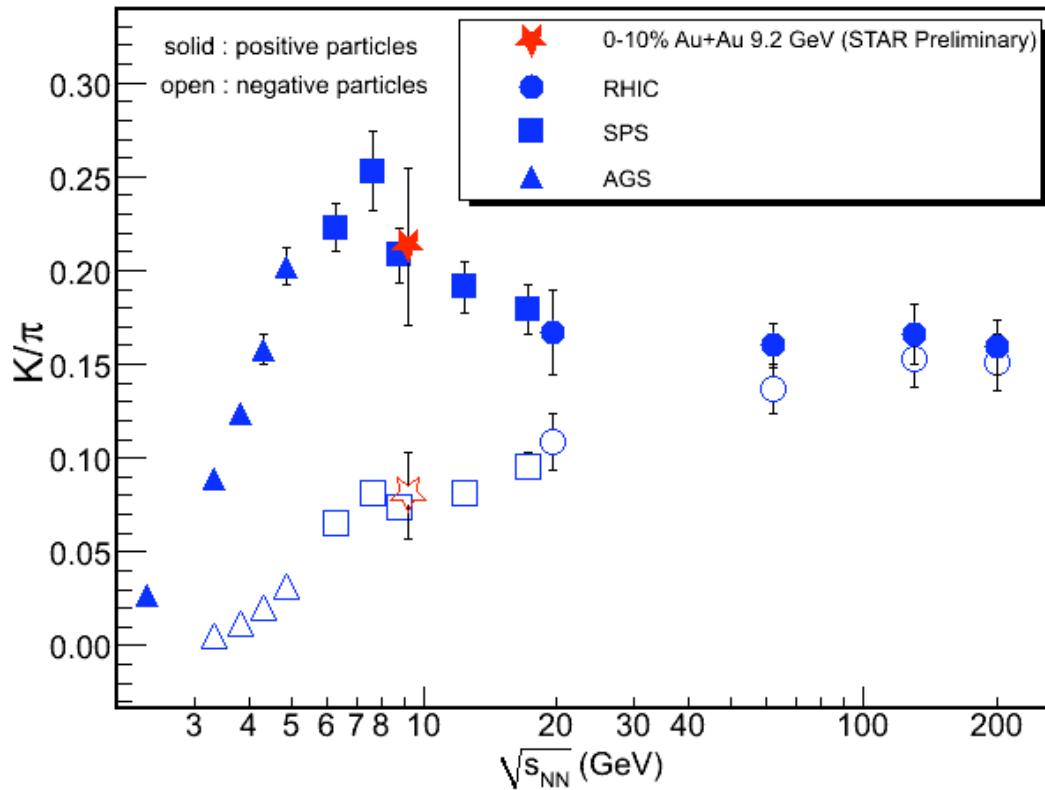
- $m_\phi \sim m_p \sim 1 \text{ GeV}$
- $s\bar{s} \Rightarrow \phi$ not $K^+K^- \Rightarrow \phi$
- $\sigma_{\phi h} \ll \sigma_{p\pi, \pi\pi}$

In the hadronic case, absence of n_q -scaling and the value of v_2 of ϕ will be small or zero.



Onward to the Critical Point

STAR: sub. to PRC, arXiv: 0909.4131

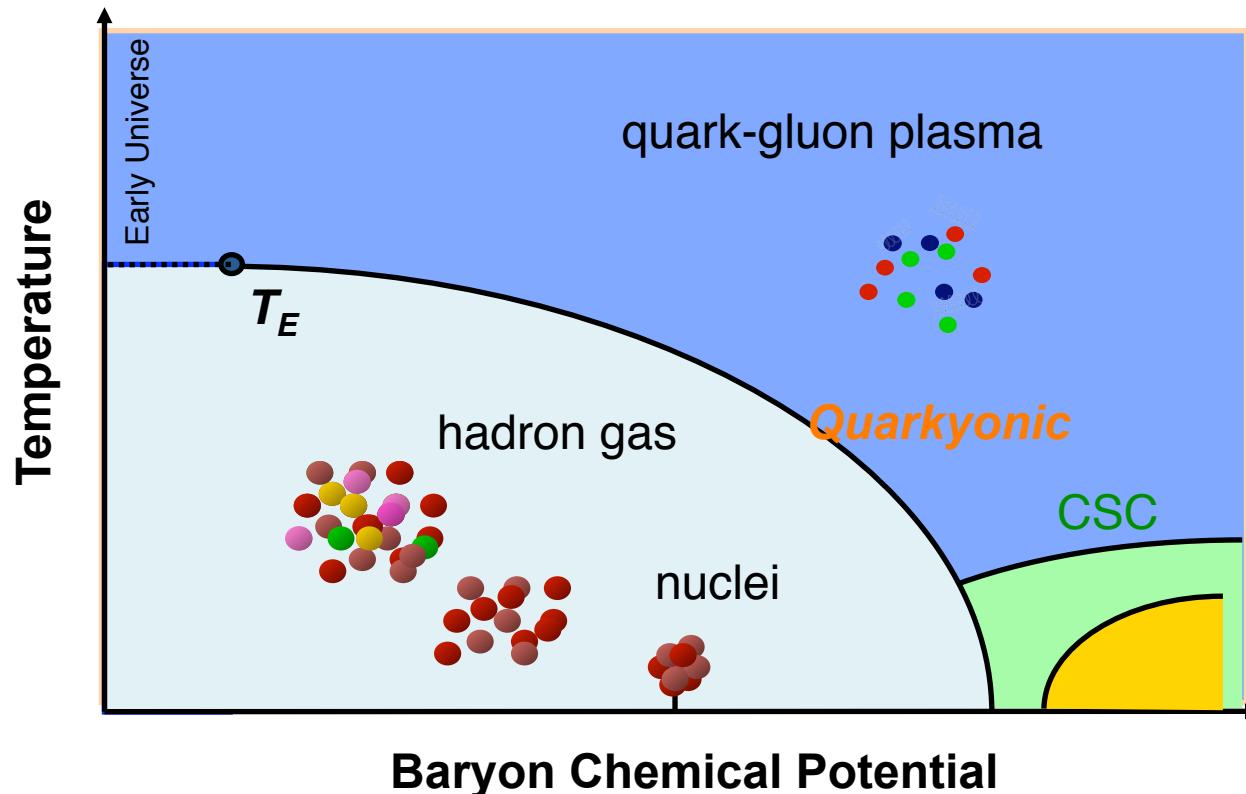


STAR: results from ~3k events in 9.2 GeV Au+Au collisions
RHIC BES program starts in run10 (PHENIX & STAR)

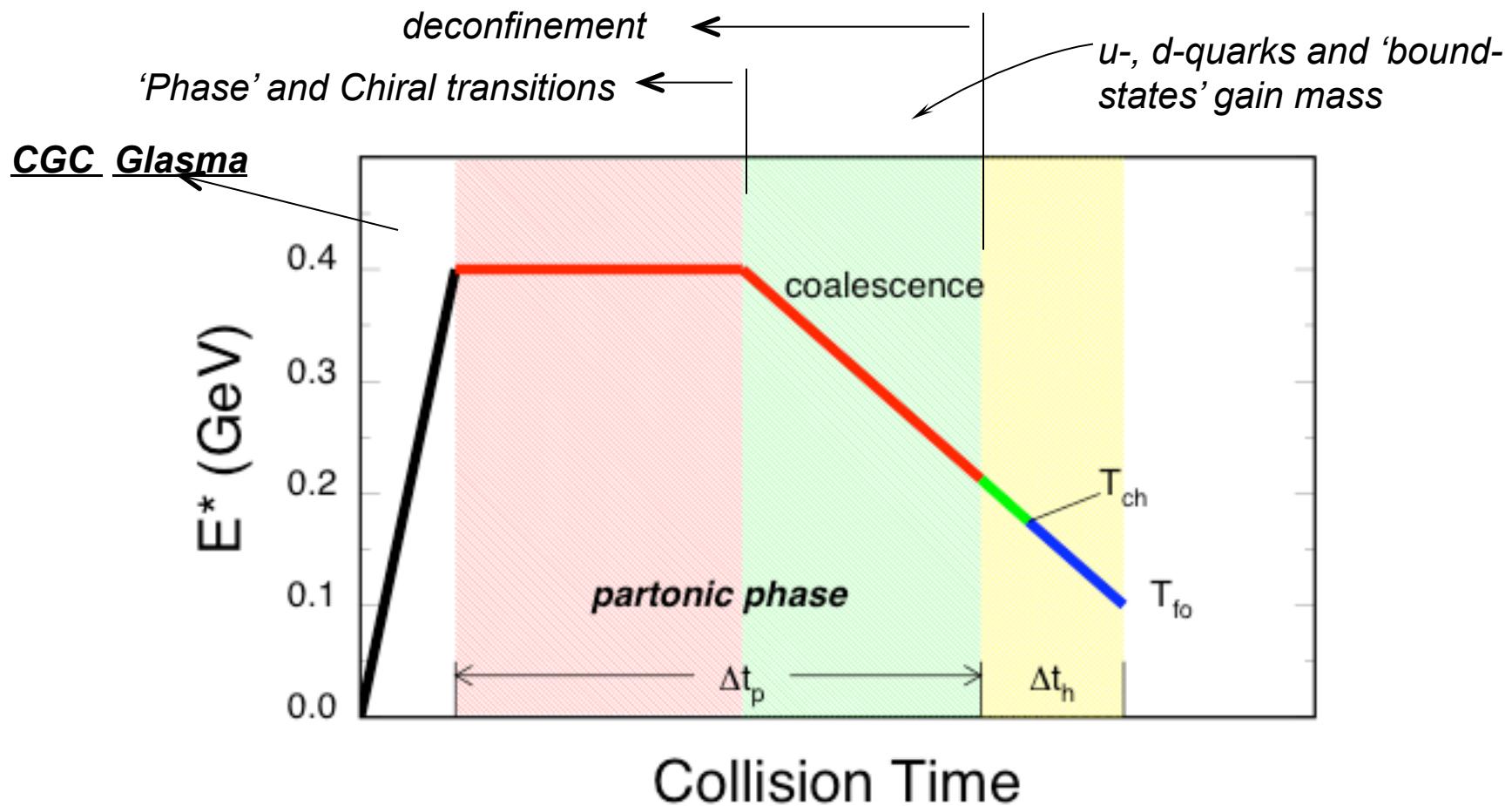


The QCD Phase Diagram and High-Energy Nuclear Collisions

Explore the QCD landscape and the structure of the matter with partonic degrees of freedom.



Collision Time - a picture for RHIC



- 1) Coalescence processes occur during phase transition and hadronization;
- 2) The u -, d -quarks and 'bound-states' gain mass accompanied by expansion;
- 3) **Early partonic thermalization and its duration need to be checked.**